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DESIGN FOR A LASER RANGEFINDER

by

T. G. Bergman
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ABSTRACT. In order to design a laser rangefinder, it is necessary to predict the effect that a change of any variables will have on the expected performance. Preliminary aspects of the overall design are discussed giving a general background in the current state of the art. A derivation of the relationship between the parameters in what is generally called the "range equation" is shown. Methods for determining the parameters are presented and it is shown how the parameters affect the performance specification. The second half of the thesis computes the range equation and presents the design for a rifle rangefinder. The intent is to give a specific example for the material in the preceding discussion, and also to report on this design, which is being developed as a prototype model for military use. The rifle rangefinder is a portable instrument designed to be mounted on a rifle in place of the usual telescopic sight. It is extremely lightweight (less than 5 lb) and sets the rifle to the correct elevation semiautomatically.

This report is a facsimile of a thesis prepared in partial satisfaction of the requirements for a master's degree of science in engineering. It is published at the working level for information only.

U.S. NAVAL ORDNANCE TEST STATION

China Lake, California

December 1964

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FOREWORD

A laser rangefinder is an instrument that measures the range or distance of an object by emitting a short burst of light in the direction of the object and detecting a small portion of the light reflected back. The elapsed time between emission and receipt of the reflected light is proportional to the distance.

The equipment used and personnel taking part in the investigation were provided by NOTS; the author then used the information gleaned during the study as the material for a thesis in partial satisfaction of the requirements for a degree of Master of Science in Engineering.

The work was done during the period July 1963 through July 1964 and was supported by Range Instrumentation funds as part of WepTask RMWC-54 046/216-1/F009-13-03 (Problem Assignment 2). Although the work was done as part of an official project, the thesis was put in final form at the author's expense. This report is a facsimile of the thesis published at the working level for information only.

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LIST OF SYMBOLS USED, DEFINITIONS, AND UNITS

$\mathring{A}$	Angstrom $\equiv 10^{-10}$ meters
A_o	object area meters^2
A_R	area of receiver meters^2
c	speed of light 3×10^8 meters/sec
d	diameter of laser rod
D	diameter of objective lens
e	charge on electron 1.60×10^{-19} coulombs
f/no.	f number (for a lens, f/no. = diameter/focal length)
$F_{\delta t}$	false alarm rate during δt
$F_{\Delta t}$	total false alarm rate
h	Planck's constant 6.63×10^{-34} joule-sec
i	noise current coulombs/sec
I_N	noise current electron/sec
k	Boltzmann's constant 1.38×10^{-23} joules/°K
K_o	reflection efficiency of object
K_R	collection optics efficiency
K_T	transmission of transmitter optics
K_λ	transmission of optical filter
n	index of refraction
$\bar{n}$	mean number of electrons recorded during time resolution period δt due to noise
$\bar{N}$	mean number of electrons required in signal pulse
n_t	threshold number of electrons
NEP	noise equivalent power watts

P_B	background power	watts/ster/m^2/A
P_N	incident power which is noise	watts
P_T	power output of laser (transmitter)	watts
r	ohms resistance of detector	ohms
r_1	lens radius of curvature for the first surface encountered by the incident light	
r_2	lens radius of curvature for the second surface encountered by the incident light	
s	estimated standard deviation of mean number of electrons received in δt	
S	sensitivity of detector	amp/watt
s.a.	lateral diameter of blur circle due to spherical aberration.	
S/N	ratio of signal to noise	
t	time	seconds
T	transmission, also used as a subscript denoting transmitter	
T'	absolute temperature	°K
v	noise voltage from detector	volts
x	$x = \frac{1}{s}(n_t - \bar{n})$	
y	$y = (\bar{N} + \bar{n} - n_t)(\bar{N} + \bar{n})^{-\frac{1}{2}}$	
z	$z = \Delta t/\delta t$	
α	light absorption	km^{-1}
$\dot{\beta}$	rotation rate of spinning reflector Q-spoiler	revolutions/sec
δf	electrical bandwidth of circuitry	sec^{-1}
δR	range resolution	
δt	resolution time	sec
Δt	range gate time	sec
$\Delta\lambda$	optical filter bandwidth	Å

ϵ	angle between transmitter, object and receiver; on an integrated transmitter-receiver this angle is zero
η	quantum efficiency of detector
θ	transmitter beam spread radians
λ	wavelength meters
μ	micron $\equiv 10^{-6}$ meters
π	3.1416
σ	standard deviation
ϕ	natural beam divergence of a laser radians
ω_{OR}	solid angle subtended by the object as seen from the receiver steradians
Ω_R	solid angle field of view of receiver steradians

Chapter 1

LASERS AND RADAR

Laser Rangefinders, like radar, measure distance by measuring the time necessary for electromagnetic radiation to travel to the object in question and back to a receiver at a speed equal to c/n where n is the optical index of refraction of the medium and c is the speed of light in vacua. The first difference from radar is that the transmitter power generator is a laser, which emits radiation with wavelengths in the optical region. This, of course, necessitates other differences, such as the type of detection system used. Since lasers are optical devices, they cannot be adapted directly to the function of ranging from only a knowledge of electrical engineering. The theory of range finding needs to be rederived on an optical basis, and requires for its solution the engineering techniques encountered in optical design.

Lasers have only been in existence during the last five years. There are three general classes: gaseous lasers, semiconductor lasers and solid or partially viscous lasers. The gaseous type is made from

a long, thin tube filled with some gas or combination of gases and has usually been used where size is not prohibitive, where high energy output is not necessary or where continuous operation or a more stable frequency is desired. The other two types are smaller and are capable of higher power outputs on a pulsed basis. The solid lasers are most popular for rangefinder application; they are generally in the form of a crystal or glass rod and the energy is put into the rod (the rod is "pumped") by reflecting the light from a flashtube into the rod. The resulting laser emission can be millions of times brighter than the sun at that wavelength.

A laser rangefinder has many advantages over conventional radar. Laser light is nearly monochromatic, that is, all the photons emitted have nearly the same wavelength; thus by filtering out all wavelengths except laser wavelengths from entering the detector, background radiation, such as scattered sunlight, can be almost entirely eliminated. Lasers can be designed so that the output light is collimated into a very narrow beam which means that reflections from objects outside the beam do not interfere with the desired reflected signal, a common problem in radar called ground clutter. For a given energy input, the distance light will travel can be greatly increased by collimation. An interesting comparison can be made by considering the radiant intensity or power density in the output from the transmitter. The 430 MC radar under construction at Arecibo, Puerto Rico, using a 100 ft. disk and 4.5 megawatt peak power has a power output of 10^{11} watts per steradian. A 4.5 MW laser can easily have a power output of 10^{15} watts per steradian. Peak powers in excess of 100 times 4.5 MW can also be

achieved. These characteristics provide new opportunities for invention and exploitation.

WAVELENGTH DEPENDENCE OF LASERS

There are many kinds of laser materials and each emits light of a wavelength which is unique to the material. The wavelengths can be computed from the energy difference ΔE of the emitting energy transition. This energy difference is affected little by a change in temperature and under normal temperatures does not vary by more than one part in ten and for most lasers much less than that. Semiconductor lasers vary much more with temperature than do ruby or glass lasers. A desirable laser has the following properties: good energy conversion efficiency; the product of its maximum output and the detector's sensitivity is high; it transmits well through the atmosphere or other intervening media; its size, availability, threshold energy for lasing, etc. fits the requirements of the project well. If the dominant noise source is background radiation, then the background should be low at the laser wavelength since background of the same wavelength as the laser light cannot be filtered out.

From Fig. 1 it can be seen that fortunately there are windows through the atmosphere[2] at the popular, laser wavelengths, 1.06μ (neodymium doped glass), 0.694μ (ruby) and 0.530μ (the second harmonic wavelength for neodymium). The maximum transmission of light through the ocean is in the blue-green region, Fig. 2, so that second harmonic neodymium glass lasers might be considered best for this

application.[3, 4, 5] The wavelength of gallium arsenide semiconductor lasers (0.83μ) also lies in an atmospheric window. More research on lasers of this material is important because of their small size and high efficiency. Latest reports show gallium arsenide to be about 40% efficient in converting electrical input to light output power. Ruby, a common laser material, is no better than 0.1% efficient. Neodymium-glass is about 0.5% efficient when used in the infrared, but the efficiency drops an order of magnitude in the second harmonic and even more for higher harmonics. Private communications with Dr. Hugh Quin of International Business Machines indicate that the output of gallium arsenide may soon be in the high power region by having one gallium arsenide laser pump into another, thus operating as an amplifier; or gallium arsenide lasers may also be used as a pump source for other lasers.

WAVELENGTH CONSIDERATIONS FOR DETECTION

Looking at the next graphs, Figs. 3 and 4, the merits of various wavelengths can be seen. Fig. 3 shows how the sky irradiance changes with wavelength, and Fig. 4 shows the ability of photomultipliers to detect various wavelengths.* Photomultiplier tubes make by far the

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* For helpful information on photomultipliers, see the technical brochures from the following companies:
EMI Electronics, Ltd./U.S., North Hollywood, Calif.
Electro-Mechanical Research, Inc., Princeton, N. J.
ITT Industrial Labs., Div. of International Telephone and Telegraph Co.
Radio Corp. of America--especially RCA phototubes and photocells, technical manual PT-60, Lancaster, Pa.

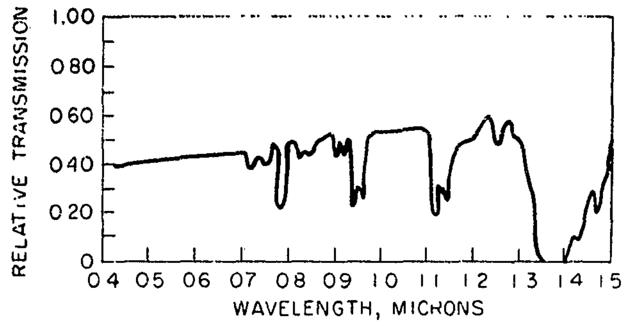


Figure 1. Atmospheric Transmission

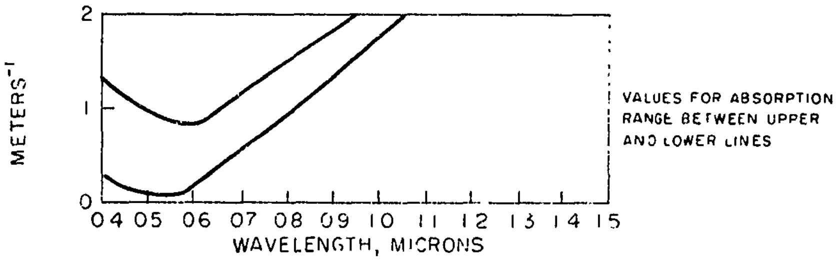


Figure 2. Sea Water Absorption

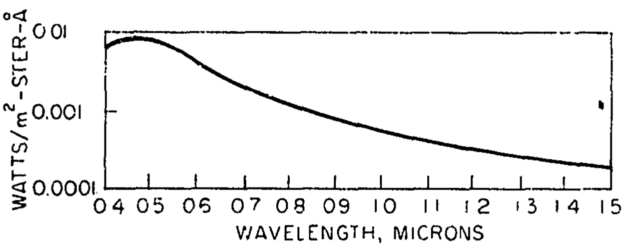


Figure 3. Sky Irradiance

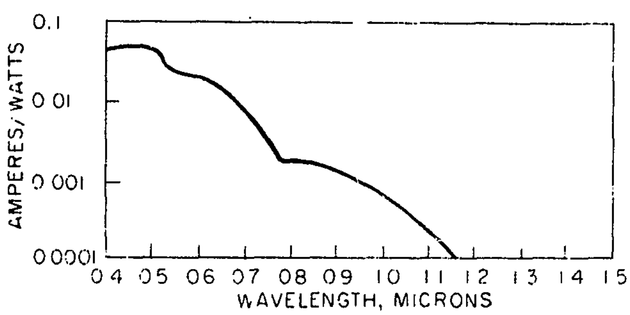


Figure 4. Photomultiplier Sensitivity

best detectors for the visual wavelengths. Only at wavelengths less than 1.06μ does any other form of detector perform nearly as well. At 1.06μ the performance of silicon detectors which are specially tuned to have maximum sensitivity there equals that of photomultipliers. The internal noise generated by silicon detectors is indeed much greater than that of photomultipliers, but the quantum efficiency--the ability to convert incoming photons to electrons--is so much better that it compensates for the increased noise. The respective quantum efficiencies of photomultipliers and silicon at 1.06μ are 0.04% and better than 80%.* The disadvantages of photomultipliers are their large size, the very high supply voltages necessary, and their construction, which for some applications leaves them relatively fragile.

COMPONENTS

The components of the rangefinder can conveniently be classified according to their function. These are shown in the block diagram, Fig. 5.

Transmitter

The laser pump power supply usually consists of a battery or rectified alternating voltage with capacitor output. It is at this point that the system's input energy is usually calculated. Capacitors are high efficiency devices and can be treated with small error as

* Technical information brochures from Electro-Nuclear Labs., Inc., Mountain View, Calif.

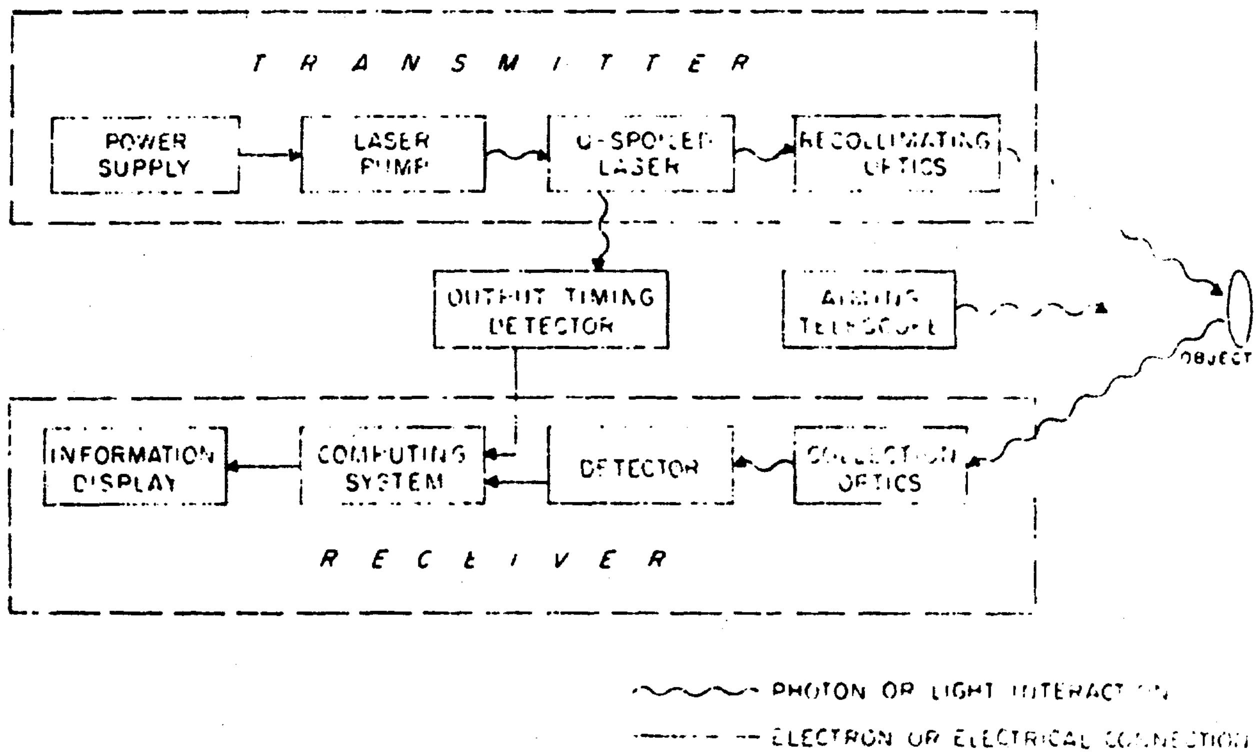


Figure 5. Laser Rangefinder Components

having efficiencies of 100%. This means that the input energy per pulse to the laser can be calculated as $\frac{1}{2} CV^2$ where C is the capacitance and V is the potential difference applied.

When a flashtube is used as the laser pump, it is connected to the capacitor and, when triggered, converts the capacitor's stored energy into light which pumps the laser with a spectrum depending on the flashtube gases used. For semiconductor diode lasers the capacitor pulse is applied to the junction of the semiconductor materials.

A rangefinder laser should always be Q-spoiled,[6] "Q-spoiling" or "Q-switching" generates a short pulse with high peak power and both of these conditions are necessary. The pulse duration, or at least the rise time of the pulse, should be sharp so that distances can be resolved. The rise time must be on the order of, or shorter than, $2 n \delta R/c$ where R is the desired range resolution, n is the index and c is the speed of light. That power is the quantity of interest rather than energy can be seen by realizing that only that energy which is received during some definite time interval can be used as signal, and energy per unit time is, of course, power. It is possible to use auto-correlation schemes which have been developed for radar, to determine the shape (amplitude versus time) of the transmitted pulse and to determine the effect of the target and intervening medium (atmosphere) on the pulse shape. The return signal can then be extracted from the noise knowing its expected shape. When this is done the distinction between energy and power becomes less clear and it might be argued that energy is more important. Auto-correlation techniques have their chief value in radar where repetitive pulsing is used. It can be shown that to

operate the laser in other than the single pulse mode is at the present wasteful of energy, if not beyond the state of the art.

Earlier it was stated that the energy delivered in a given time period determines the average power. A complete discussion of what that time period should be and how it is related to pulse length and other parameters makes up a good part of this paper. The time is usually determined electronically and may include only part, or all, of the pulse. In order to determine time precisely when a pulse longer than the resolution time is used, it may be necessary to measure time from a given point on the wave shape. This is actually a simplified form of correlation counting.[7] The limit on how short this time period can be and how precisely range can be determined or resolved is affected by three major factors. Atmospheric turbulence and inhomogeneity affect the time of arrival of the return pulse. The time response of the detector and its processing circuitry and the electronic bandwidth limit the time. Third, the laser pulse itself may be too long. These points will be elaborated on later.

A means to further shorten the laser pulse beyond what Q-spoiling does is to use a laser amplifier. Putting a pulse of light from one laser into another which is already pumped to an excited state will also stimulate emission from that laser. Since the front part of the stimulating pulse arrives first, it will be amplified most. Most of the amplifier's stored energy will have been used by the time the trailing edge comes along so that the resulting pulse has a sharper rise time and a greater energy density than the original pulse had.

Since the beam direct from the laser has a divergence which is greater than necessary or desirable, and because a narrower beam means higher power density and greater range, the direct output must almost always be further collimated. A somewhat detailed discussion of the limits on improvement that can be expected is given in Chapter 4.

For precise range measurements it is necessary to use a detector to measure precisely the time of pulsing. This is best done by appropriately observing the light pulse itself. Time measurements begun when the flashtube is triggered are unreliable because of variations in excitation time.

Receiver

The light reflected from the object is collected by auxiliary optics, which focus the light on the detector. The received intensity is directly proportional to the effective area of the receiving telescope. Of course, received background radiation increases in the same proportion, but since noise increases by the square root of noise amplitude, as will be shown in Chapter 2, the total gain when background is the predominant noise will only be proportional to the change in diameter of the collecting optics.

The computing system usually consists of a flip-flop circuit which is turned on by the transmitter detector and turned off again by the receiver detector. The flip-flop circuit starts and stops a timing device or clock such as a crystal controlled oscillator. The elapsed time then is displayed as range.

An alternate method for computing the range has been described by the author.[8] It has a more limited application but offers some

advantages to the clock method. Simply, it consists of a rotating mirror whose speed of rotation is known. The optimum position for this mirror would be on the shaft of the mirror used to Q-spoil the laser. The received light would be reflected from the mirror and diverted through an angle which is proportional to the range. The transmitter fires when the Q-spoiled shaft is at a fixed angle. If this is called the fiducial angle or 0°, then γ, the angle at which the light is received, is

$$\gamma = 4 \ n \ R \ \dot{\beta}/c$$

The factor 4 appears in this equation because of the travel time to and from the target and because of the equal angles of incidence and reflection from the mirror.

Chapter 2

INTRODUCTION

To approach the problem of knowing what size power supply is needed, how much cooling is necessary and what the optical design should be, calculation must be made of the laser light output requirement. This calculation is based on three categories of variables: first, parameters set by the objective of the project and considered to be fixed, second, parameters which are themselves to be calculated or determined experimentally, and third, parameters which would be desirable if they could be incorporated. The first category might include the maximum distance over which range information will be required, the repetition or sampling rate, the precision of the measurement, the target's size and reflectivity, the percentage of times that the target can be allowed to be missed or not detected, the percentage of incorrect readings or false alarm rate, and perhaps the maximum package size and weight. The second group requires the most research to assess and includes description of the detector, atmospheric attenuation, background brightness, attenuation by the optics,

signal to noise ratio and cooling rate. The third area is the part most affected by the design. A good design will allow for increased range, more precision, portability, reliability, and all other aspects which could make the rangefinder a better instrument.

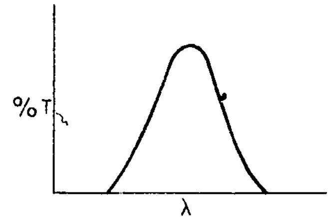
In deriving the power requirements the noise present will be computed first, the percentage of light output which is received and used as signal will be found, and then the necessary signal to noise ratio will be computed. Only after all these variables are included into a single equation can a design be properly accomplished. For instance, in different cases such things as the beamwidth or the area of the receiver may appear as the square, the cube or even the fourth power, and of course this will tremendously affect the physical design.

BACKGROUND NOISE

The power, or flux per second, P_B, which is always present as background in the field of view of the receiver has a spectral dependence and must, therefore, be expressed per unit of wavelength at a given wavelength. Since the dependence is not strong it may then be multiplied directly by the bandwidth $\Delta\lambda$ of wavelengths being looked at with negligible error. That is, for narrow bandwidths the background power is nearly enough independent of wavelength to be taken outside the integral.

$$\int_{\lambda_1}^{\lambda_2} P_B(\lambda)\, d\lambda \approx P_B(\lambda)\, \Delta\lambda$$

Actually, of course, the wavelengths looked at (bandpass of the filter) are not rectangular, but are more as shown for the percentage of light at a given wavelength, and some sort of numerical integration is appropriate.



Noise due to background radiation is a direct function of the area of the receiver A_R or telescope, and the angular field of view over which it receives background radiation. This will be equal to the field of view of the receiver Ω_R minus the solid angle subtended by the object at the receiver ω_{OR}. Power must also be multiplied by the efficiency K_R of the collection optics and the transmission K_λ of the optical filter and the quantum efficiency η or sensitivity S of the detector. The quantum efficiency or sensitivity is taken into account because noise is conceptually most easily computed in terms of electrons on the first dynode for a photomultiplier or in the output of a detector.

(1) P_N (watts incident) $= P_B A_R (\Omega_R - \omega_{OR}) \Delta\lambda\ K_\lambda\ K_R$

(2a) I_N (electrons/sec) $= P_B A_R (\Omega_R - \omega_{OR}) \Delta\lambda\ K_\lambda\ K_R\ S/e$

where I_N is the noise current and e is the charge on an electron.

Alternatively, since the energy of a photon equals hc/λ where h is Planck's constant and c is the speed of light, incoming energy may be converted to photons per second and multiplied by the quantum efficiency to obtain electrons per second.

(2b) I_N (electrons/sec) $= P_B A_R (\Omega_R - \omega_{OR}) \Delta\lambda\ K_\lambda\ K_R\ \eta\ \frac{\lambda}{h c}$

All of the above refers to diffuse radiation within the field of view of the receiver; there could be specular reflection of the sun, for instance, on the target or other objects giving rise to much larger values of energy depending on the particular geometry and intended use but in most cases the probability of occurrence is so low as to be neglected here.

DETECTOR NOISE

Noise in the detection circuitry can be analyzed by components such as detector dark current, amplifier and load resistance noise, and read-out ambiguities. The latter can generally be designed to be negligible with standard electronic techniques. The former two which will be considered here depend on the detector.

For photomultiplier tubes, dark current at room temperatures is predominantly due to thermionic emission from the photo-cathode which is then amplified along with the signal. In the situation where the tube is cooled so that other sources of noise become comparatively appreciable, the total dark current will have dropped to a level such that there is good probability that no noise electrons will appear during the short time interval of detection and exterior noise sources will predominate.

NOISE STATISTICS

When the predominant noise is either due to thermionic emission from the photo cathode or from the photo cathode being illuminated by

a steady background, the frequency is best described by a Poisson distribution since individual electrons are emitted from the cathode randomly with respect to time.[9-13] There is a slight deviation from Poisson because not all electrons emitted reach the photomultiplier dynode and get amplified but this effect is negligible. It could also be described more basicly by a binomial distribution knowing the processes by which photons are absorbed and electrons emitted or how thermal agitation causes electrons to overcome the work function energy, etc., but the parameters necessary to do this are not readily available and the Poisson description is preferable.

During some time period, δt, there will be $\bar{n}$ electrons expected. To find out the number of electrons for threshold, n_t, an acceptable signal to noise ratio must be determined. The threshold value is set such that whenever more than n_t electrons arrive during the time period it is concluded that a signal is present or if there are less than n_t no signal is present, only noise. When an electronic device is used it is set to respond only to voltages greater than voltage corresponding to n_t electrons. A false alarm rate is decided upon, as in radar, which is the percentage of time for which a false signal is recorded due to noise. This false alarm rate is the probability, $F_{\delta t}\ (< n_t)$, predicted by the Poisson distribution.

$$F_{\delta t}\ (< n_t) = \sum_{n = n_t}^{\infty} \frac{\bar{n}^{\,n}\ e^{-\bar{n}}}{n!} \tag{3}$$

for which tables are available.[14, 15]

It is desirable to normalize this in terms of the estimated standard deviation s since $s = (\bar{n})^{\frac{1}{2}}$. Gaussian distribution tables

may be used for this for large n and n_t may be estimated by determining the parameter x where

$$n_t = \bar{n} + xs = \bar{n} + (\bar{n})^{\frac{1}{2}} \tag{4}$$

As an example, if there are ten or twenty or more electrons on the average, then ten percent of the time the fluctuation will exceed the mean. This points up the fact that we are interested only in the fluctuation in n, not $\bar{n}$ except, of course, that they are related. On a macroscopic scale the noise may be thought of as a summation of a direct current and a fluctuating, alternating current where the origin is taken at the mean d.c. level $\bar{n}$ instead of at zero so that the magnitude of the d.c. part is negated. This leads to important results such as the fact that it does pay to increase the area of the receiving optics since signal will go up linearly while background noise increases only by the square root of the increased area.

There are two time periods involved--the resolution or pulse time δt and the range gate Δt. The range gate is the time or range over which a signal might be expected or more precisely, the time during which noise electrons might be counted as signal. The resolution time is determined by one of two factors. If the precision of the range measurement is not critical, it will be the time necessary to enclose the total laser pulse--about 30 to 50 nanoseconds or 15 to 25 feet of range for a typical Q-spoiled pulse. When greater precision is necessary, that will be the controlling factor; also the rise time of the pulse will have to be less than the resolution time which may require special Q-spoiling techniques and/or laser amplifiers.

Once the maximum permissible false alarm rate for the entire range cycle $F_{\Delta t}$ is decided upon, then the minimum number of electrons $\bar{N}$ required in the return signal during the pulse time δt can be computed. Now $(1 - F_{\delta t})$ is the probability that no false alarm occurs per pulse period; if z is the number of times that Δt exceeds δt, then

(5) $$F_{\Delta t} = 1 - (1 - F_{\delta t})^z$$

thus from Eq. 3

(6) $$F_{\Delta t} = 1 - \sum_{n = n_t}^{\infty} \left(\frac{\bar{n}^n e^{-\bar{n}}}{n!} \right)^z$$

which can be solved for n_t.

$\bar{N}$, the number of electrons required for the signal is computed next. The fluctuation of N is also described by the Poisson distribution so that one standard deviation is equal to $(\bar{N})^{\frac{1}{2}}$. Determination of how far above threshold $(\bar{N} + \bar{n})$ should be depends on how often one can allow the sum of the number of electrons in the signal plus the number due to noise to add up to less than n_t, the decision or threshold level. When this occurs the signal is missed and nothing is recorded at all. The standard deviation of the total is the square root of the sum of the variances, which when $\bar{N}$ and $\bar{n}$ are each Poisson distributed is $(\bar{N} + \bar{n})^{\frac{1}{2}}$. If y is the number of standard deviations by which $(\bar{N} + \bar{n})$ should exceed n_t, then

(7) $$\bar{N} + \bar{n} = n_t + y\ (\bar{N} + \bar{n})^{\frac{1}{2}}$$

y may be determined from tables knowing the missed signal rate to be allowed and then since n_t and $\bar{n}$ are already computed, $\bar{N}$ may be computed iteratively, usually in two or three trials.

Combining Eqs. (7) and (4),

$$\bar{N} = x\ (\bar{n}) \ + y\ (\bar{N} + \bar{n})^{\frac{1}{2}}$$

Since for large $\bar{n}$, which is often the case, $\bar{N}$ is comparatively small,

$$\bar{N} \approx (x + y)\ (\bar{n})^{\frac{1}{2}} \tag{8}$$

SOLID STATE DETECTORS

Another detector which is used where infrared detection is needed and where the size and ruggedness become important is a solid state detector. In the visible, their performance is several orders of magnitude down from photomultipliers and so are not generally considered for use there. At the neodymium wavelength, 1.06μ, the only photomultiplier surface which is sensitive is Ag-O-Cs, which is classified as S-1 by the Electronics Industries Association (EIA). Its performance is roughly equivalent to a silicon detector which is properly tuned to that wavelength and amplified. Thus a silicon detector is in competition with a photomultiplier for neodymium wavelengths. Silicon detectors can be made with a quantum efficiency approaching 100% at 1.06μ and a noise equivalent power, NEP, which is low enough that the limiting noise comes from the following amplifier. Noise occurring in solid state amplifiers is usually thermal noise arising from the random agitation of molecules with an amplitude measured in terms of the absolute temperature T'. It is based on Einstein's derivation of Brownian movement and is also called Johnson noise. It has been shown to be independent of frequency up to very

high frequencies and is described by a Gaussian distribution around the mean which is zero. The estimated standard deviation s is calculated from the formula

(9) $$s = i = \left(\frac{4\ k\ T'\ \delta f}{r}\right)^{\frac{1}{2}}$$

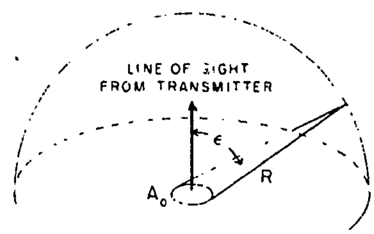
Here i = (peak current) - (average current)

and k is the Boltzmann constant, δf is the electrical bandwidth and r is the ohmic resistance of the input to the amplifier (usually, therefore, the detector resistance) since the noise in this input restor material is amplified most and therefore predominates.

OUTPUT ATTENUATION

Once the number of signal electrons required from the photo cathode is known, the equivalent output from the laser necessary to produce this can be calculated. As the power output P_T from the laser (transmitter to use the radar term) goes along the optical train, it is first modified by the percent transmission of the optics K_T. The transmitted beam has a spread that is usually a cone and measured by the angle Θ in radians; when the object area A_o is smaller in extent than the area of the cone cross-section at that range then $4A_o/\pi(\Theta\ R)^2$ of the beam is intercepted, where R is the range from transmitter to object; when the object for which range is desired is equal or greater than the cone, then $A_o = \pi(\Theta\ R)^2/4$. The object next reflects only a certain percent K_o of what is incident; if it has retrodirectional

properties this must be taken into account, or if it is diffuse, a model such as lambertian or isotropic should be assumed, in most cases a lambertian surface comes closest to actuality. Lambert derives his model based on the projected area visible to the receiver at each point on the hemisphere. Near the periphery the illuminated area is seen edge on and therefore is zero. Elsewhere the area seen increases as the angle ϵ shown on the inset decreases. It is assumed that the flux seen from A_o is proportional so that at the point where the flux is received the power is proportional to $\cos \epsilon$. The total flux emitted to the hemisphere at $\epsilon = 0$ is therefore twice the amount at that angle if the energy were assumed to be uniform over the hemisphere of surface area $2\pi R^2$.[16] The area of the receiver A_R intercepts a portion of what is



reflected and for a target or object with a surface that is assumed to reflect light according to the lambertian model the portion is $A_R/\pi R^2$, for a corner cube prism or similar object which returns the incident beam on itself without altering the original angular deviation the portion is $4A_R/\pi(R\,\theta)^2$. This is further reduced by the transmission of the receiving optics K_R, the transmission of the optical filter K_λ, and the efficiency of the photo cathode surface η. The power output of the transmitter in terms of the number of electrons required from the photo cathode is then

(10a) $$P_T = \frac{\bar{N}\ \pi^2\ \theta^2\ R^4\ h\ c\ e^{2\alpha R}}{4\ A_o\ A_R\ K_T\ K_o\ K_R\ K_\lambda\ \eta\ \lambda\ \delta t}$$

(lambertian reflector object)

(10b) $$P_T = \frac{\bar{N}\ \pi^2\ \theta^4\ R^4\ h\ c\ e^{2\alpha R}}{16\ A_0\ A_R\ K_T\ K_0\ K_R\ K_\lambda\ \eta\ \lambda\ \delta t}$$

(retrodirectional object)

Eq. 10 is used as it stands for the case where the limiting noise is generated within the detection device itself, be it dark current from the photosurface, detector junction, amplifier, load, or whatever and Eq. 6 is substituted.

For the case where the limiting noise comes from illumination of the background in the object space the following equation is to be preferred as the function of the parameters in their ratio to P_T is changed. From Eqs. 2b, 8 and 10a (for a background limited situation the receiver is generally designed so that the field of view is equal to the cone of the projected light or output divergence and for most cases ω_{OR} is negligible so that $\Omega_R - \omega_{OR} = \pi\ \theta^2/4$

$$P_T = \frac{\pi^2\ \theta^2\ R^4\ h\ c\ e^{2\alpha R}}{4\ A_0\ A_R\ K_T\ K_0\ K_R\ K_\lambda\ \eta\ \lambda} \cdot (y + x)\left(P_B\ A_R\ \frac{\pi\ \theta^2}{4}\ \Delta\lambda\ K_\lambda\ K_R\ \eta\ \frac{\lambda}{h\ c}\ \delta t\right)^{\frac{1}{2}}$$

$$P_T = \frac{(x + y)\ \pi^{3/2}\ \theta^3\ R^4}{8\ A_0\ K_T\ K_0\ e^{-2\ \alpha\ R}} \left(\frac{P_B\ \Delta\lambda\ \ h\ c}{A_R\ K_R\ K_\lambda\ \ \eta\ h\ c\ \delta t} \right)^{\frac{1}{2}} \tag{11a}$$

(lambertian reflector object)

$$P_T = \frac{(x + y)\ \pi^{3/2}\ \theta^5\ R^4}{32\ A_0\ K_T\ K_0\ e^{-2\ \alpha\ R}} \left(\frac{P_B\ \Delta\lambda\ \ h\ c}{A_R\ K_R\ K_\lambda\ \ \eta\ \lambda\ \delta t} \right)^{\frac{1}{2}} \tag{11b}$$

(retrodirectional object)

Another case which might be encountered is where the limiting noise is due to energy which is reflected from the target itself. A similar derivation to that shown above should then be followed.

Fig. 6 shows how the power required changes with range for various values of atmospheric absorption. Fig. 7 gives a similar graph for the case where the object is larger than the laser beam and instead of an inverse fourth power law, the inverse square law holds.

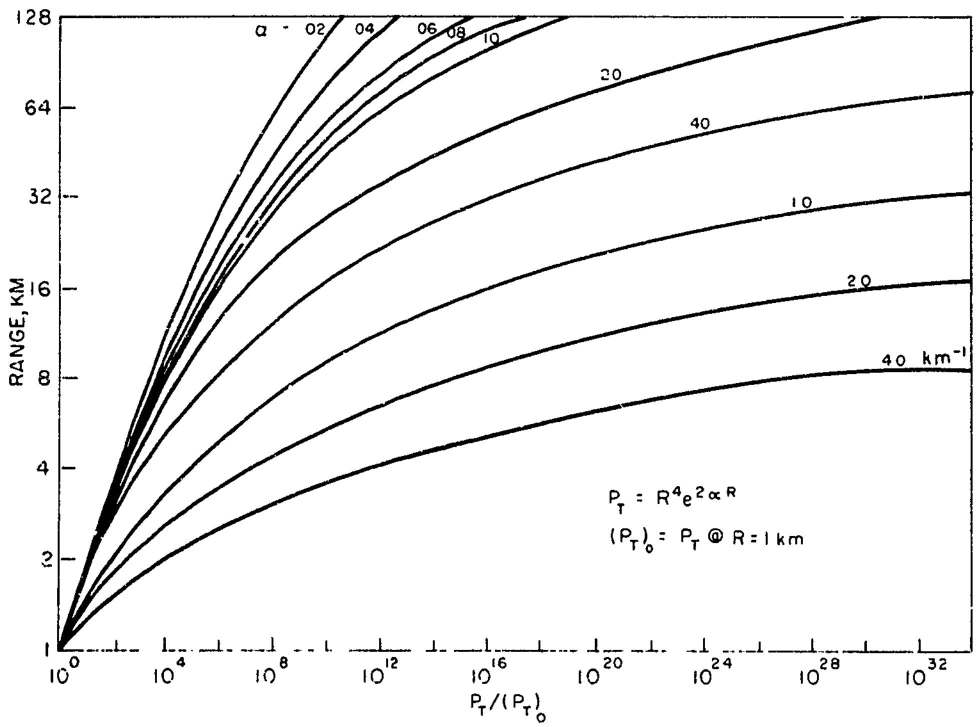


Figure 6. Power versus Range

This graph shows how power varies with range for various values of atmospheric absorption. In this case the laser beam is larger than the object.

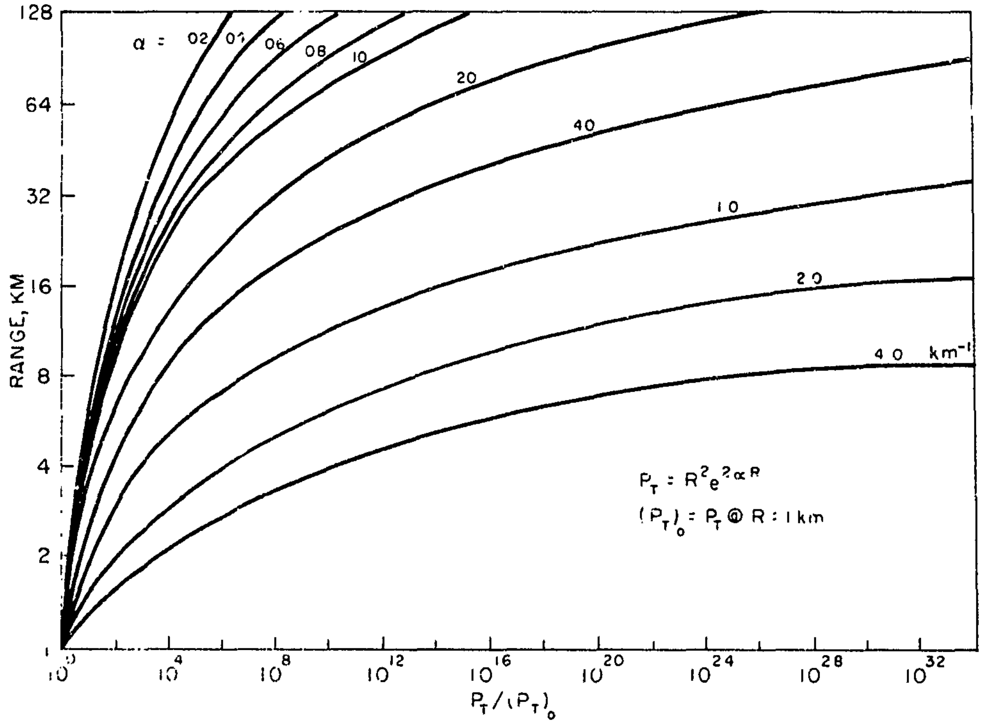


Figure 7. Power versus Range

This graph shows how power varies with range for various values of atmospheric absorption. In this case the laser beam is smaller than the object.

Chapter 3

NEED FOR RIFLE RANGEFINDER

These last two chapters describe an actual design for a laser rangefinder. This chapter derives the power requirements as a specific example of how to apply the ideas developed previously. In Chapter 4 the mechanical and optical details for the design are presented.

In the Armed Forces, there is need for a portable instrument which can determine range accurately. The author determined that this need could be met by using a laser and proceeded to determine specific goals for such an instrument. Consultation with Marine and Navy personnel and the reading of Army field manuals[17, 18] showed that if an instrument could be developed which was light enough it would have extensive use in a myriad of projects, such as tank fire control, forward observing, mapping reconnaissance, and sniping, to name a few. Perhaps the person needing the smallest rangefinder of all is the sniper, and it was decided to design a prototype for this use first.

DESIGN GOALS

A sniper's mission often involves situations where a single, long range rifle shot is the only chance he has. It is important that this shot be accurate as it will alert the enemy who will then seek cover. A second or third shot will likely give away the sniper's position. Using special ammunition and specially bored rifle barrels, a sniper often shoots from long distances. Since a bullet drops a great deal at the longer ranges, the major reason for a miss was found to be the rifleman's inability to properly assess the longer range (e.g. 1,000 yards). It is thought possible, however, that a sniper might attempt shots at a range of 1,000 yards if he knew the range, therefore the design goal was set for maximum range of 1,000 yards. It was decided that no greater accuracy than 50 feet in range would be needed and no information closer than 200 feet would be used.

The lightest existing laser rangefinder to date weighs in excess of 25 pounds including an external battery pack. However, in order to be of use to a sniper, for whom the rangefinder could only be one of many pieces of gear, the laser could add no more than 5 pounds to the rifle. This fact is borne out by the dismal failure of the infrared snooper scope. It works quite well but because it weighs 27 pounds no one was willing to carry it. In spite of the fact that several companies did not think that a laser rangefinder could be built weighing less than 15 pounds at the present state of the technology, a design was attempted and has now been successfully accomplished.

The false reading rate should be kept extremely low, say one per thousand although the missed rate could be higher, maybe 25 per thousand, since the sniper can simply measure the range over again.

Another desired goal was to have the range information display be readily usable. While present ideas all use a crystal controlled oscillator to time the pulse and then display this data on external meters, the goal for this design was to allow the sniper to keep his eye on the object at all times while range is being obtained.

Security is a design goal. The act of ranging should not alert the enemy.

Ruggedness and a minimum of maintenance or supplies such as replacement batteries are obvious requirements.

ENERGY CALCULATION

Object

The most difficult object for the rangefinder to encounter will be that of a man wearing absorbent clothing and presenting as little perhaps as an 18 inch diameter area at 1,000 yards. The clothing would typically absorb all the light incident upon it and reradiate perhaps as little as ten percent back. Buttons or other objects reflecting specularly would in general reflect in directions other than toward the receiver and thus would subtract from the effective area of the 18 inch diameter. The percentage of specularly reflecting area, however, will probably be negligible.

The best estimate of the diffusely reflected energy distribution in space is that it will all be reflected back into a hemisphere

toward the laser. The distribution within this hemisphere is most closely approximated by a model due to Lambert where the radiation back into the hemisphere is zero at the periphery and maximum at the receiver. As shown previously the maximum is exactly twice that which would be expected for an emitter radiating uniformly into the hemisphere. Thus, the incident energy is reduced by the factor.

$$\frac{2\ (\text{surface area of hemisphere})}{K_0\ (\text{effective aperture area of receiver})}$$

Background Radiation

Although the worst case for detectability through a riflescope, (least contrast between object and its background) is when the object is in a dark forest or shadow, the worst case for the rangefinder is when the object is silhouetted against a bright background. The brightest probably background will be a cloud filling the field of view of the receiver, made bright by scattered sunlight. As in Eq. (1) the amount of noise power thus entering the receiver will be

$$P_B\ A_R(\Omega_R - \omega_{OR})$$

where

$$_{OR} = A_o/R^2$$

Determination of the correct value for P_B is a formidable task, one, however, which should be done quite thoroughly in order to obtain a meaningful value. To investigate the general case properly would require another thesis. Since the subject is covered thoroughly in the literature it will suffice to simply point out sources of

information and make a few general comments, even though background brightness must inextricably be part of the subject of laser range meters. The bibliography is not intended to be complete, but some of the references listed do have comprehensive bibliographies.[19-22]

The major problem with determining background light level is that it varies constantly as a function of so many parameters that no two sources of information agree. This changing light level also makes it difficult to establish even a probable worst case although this must be done before the laser can be designed.

In this problem of the rifle rangefinder, it is improbable that range will be required at an elevation angle greater than 15 or 20 degrees. The drawing, Fig. 8, shows the conditions for which ranging will be most difficult. The sniper is shooting uphill, through an absorbing atmosphere such as haze or light fog at a small object which has a bright background surrounding it.

Since the percentage of total shots which will have the combination of high angle, foggy day, and bright clouds over the entire field of view is very small, it will be reasonable to choose a rather liberal value for P_B. A value of 3×10^{-4} watts/m^2-ster-$\mathring{A}$ is chosen as a value to design for at 1.06μ and 10^{-3} at 0.59μ with values interpolated from these two using the graph shown, Fig. 9, for other wavelengths.

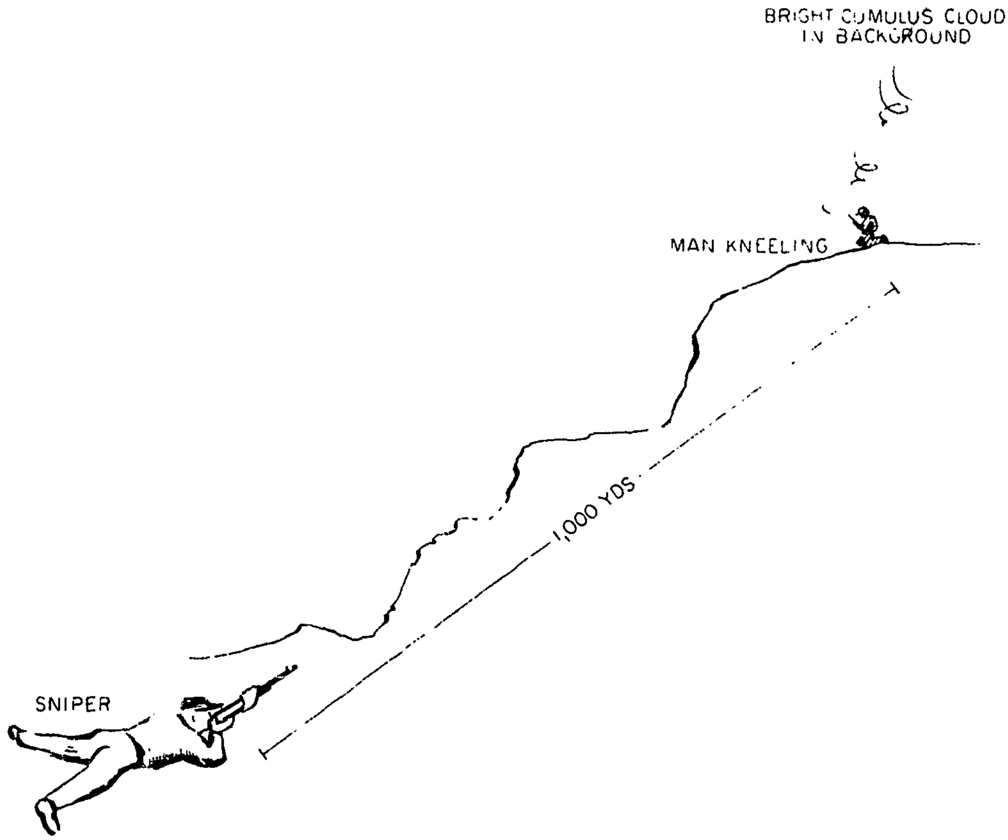


Figure 8. Worst Case for Which Rifle Rangefinder Is To Range Accurately

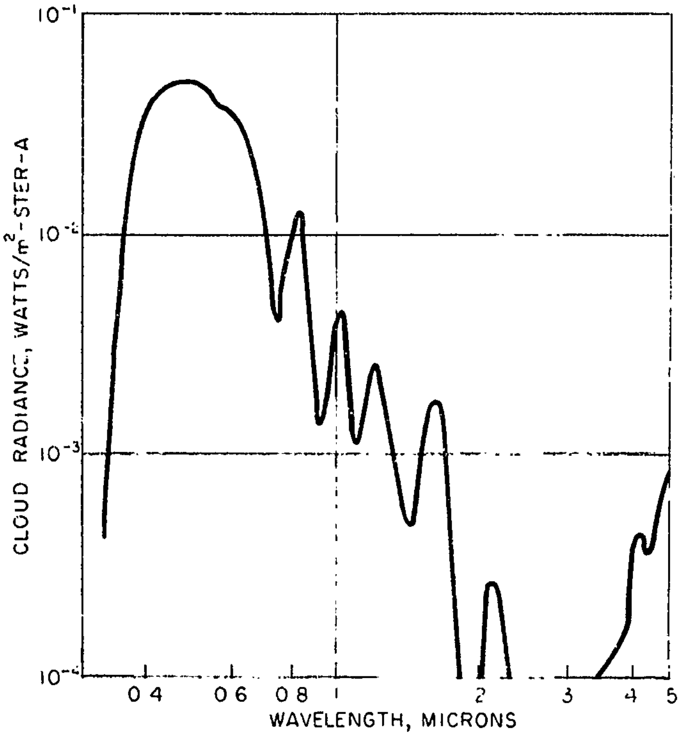


Figure 9. Typical Spectral Distribution of the Radiance from a Sun-Illuminated Cloud

ATMOSPHERIC TRANSMISSION

The transmission of laser light through the atmosphere to the object and back again, is computed from the expression $e^{-2\alpha R}$ where $R = 1{,}000$ yds = 914 meters.[23, 24, 2] The metric system is preferred, but since range estimation for rifles has been in yards, this will be used for the first prototype's readout display.

The comments in the preceding section on the variability of P_B also apply to α. Normally α is a very powerful factor (see Figs. 6 and 7) and knowing the exact value of P_B, since it appears in the square root of the range equation, is of lesser consequence than knowing α. Here, however, because of the short distance involved and the small amount of atmosphere to be travesed, the opposite prevails. A typical value for the absorption coefficient is 0.05 per km on a clear day, but if a value as different as 0.1 were used, the difference in total transmission would only change from 91 to 83 percent. On the other hand, since a sniper doesn't especially limit himself to clear weather conditions and even though R is exceptionally small, α may become quite large. As a guide the following table gives roughly the visibility limit and corresponding α for various weather conditions. Using the table as a basis for decision and supposing that a sniper would want to see in excess of 4,000 yards before attempting to shoot an object at 1,000 yards, the value for α is seen to be 1, making the total transmission 16% at visual wavelengths. Referring to Fig. 1 in the 1st chapter, transmission at 1.06μ would be about 20%.

Values of Extinction Coefficients for

the International Visibility Code*

Code Indices		Max. Visible Distance (Upper Limit)	α Extinction Coefficient (Lower Limit)
0	(dense fog)	50m	80km^{-1}
1	(thick fog)	200	20
2	(moderate fog)	500	8
3	(light fog)	1km	4
4	(thin fog)	2	2
5	(haze)	4	1
6	(light haze)	10	0.4
7	(clear)	20	0.2
8	(very clear)	50	0.08
9	(exceptionally clear)	280 (pure air)	0.014 (pure air)

LASER MATERIAL

Concomitant with the goals of light weight and security, neodymium-doped rare earth glass which emits light of 1.06μ wavelength was chosen for the laser material. During darkness, a very definite beam of red light can be seen from the laser when ruby is used, and it is possible that someone might be looking in the direction of the laser when it is fired. Also, the threshold input energy level for

* Taken from Van de Hulst, H. C., "Scattering in the Atmosphere of the Earth and the Planets." This paper is included as Chapter III in a book The Atmospheres of the Earth and Planets, ed. by G. P. Kuiper, Chicago: Univ. of Chicago Press, 1947.

lasing is higher for ruby than for neodynium. While it is true that ruby light can be detected more easily (the quantum efficiency of photomultipliers is two orders of magnitude better at .5943μ than at 1.06μ) it will be seen later that for energy inputs to Nd equaling the threshold value for ruby, a 1,000 yard range can be obtained anyway, so that other arguments are invalid. Also, recent developments in solid state silicon photodetectors make a solid state detector as good at 1.06μ as a photomultiplier at the same wavelength.* A detector and amplifier require less space than a photomultiplier and high voltage power supply. Nd in a $CaWO_4$ crystal has a lower threshold, but is not as rugged as glass and is very much more expensive.

Performance from other types of lasers has not advanced sufficiently to equal that of any of the above mentioned materials.

Gallium arsenide injection lasers were not considered because, for room temperature operation, at present, they do not exhibit high enough power outputs. To carry enough coolant for even a half day's operation would make them bulkier than Nd and would require refills which makes coolants impractical.

RECEIVER APERTURE

The receiver area is a parameter that will be discussed to some degree in this chapter and also in the next. The maximum size of the

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* Study by Autonetics, Div. of North American Aviation, to be published.
Also private conversations with Electro-Nuclear Corp. confirmed this.

receiver is determined primarily by the bulk which can be tolerated by a sniper on his rifle. Somewhat arbitrarily, it is decided that a 9 cm diameter would not be too clumsy, making A_R = .00636 m^2.

SUMMARY

At this point it seems wise to summarize, according to the outline in the introduction to Chapter 2, parameters pertinent to range without considering size and weight.

Parameters set by goals of project		Variables determined so far from the goals		Variables yet to be set by design or state of the art
R	914 meters	λ	1.06μ	K_T
δR	15 meters	P_B	3 X 10^{-4} watt/ster-m^2-Å	K_R
ΔR	731 meters	α	1	K_λ
$F_{\Delta t}$	0.1%	A_R	6.36 X 10^{-3} m^2	$\Delta\lambda$
K_o	10%			η
ω_{oR}	.5 X 10^{-6} ster			Ω_R
δt	10^{-7} sec			Θ
z	50			P_B

Having decided upon 1.06μ, there are two leading detectors from which to choose. A new ruggedized, S-1 response photomultiplier has been developed which is only 2 cm in diameter and 9 cm long.* The quantum efficiency at 1.06μ is only 0.0004 while that of a silicon detector is about 0.5. For this case, where the background radiation is so high as to make the photomultiplier's low internal noise of no significance the semiconductor detector is by far the best choice. The usual reason for choosing photomultipliers over photodiodes is because of the large thermal or Johnson noise in the diode and its amplifier. In this case, however, the background illumination is such as to make the advantages from a photomultiplier's low noise of lesser importance.

Internally generated noise from the silicon detector may be calculated from the equation for thermal noise.**

$$i = \left(\frac{4kT'}{r}\right)^{\frac{1}{2}} \tag{12}$$

since $T' = 300°$ and r is 5×10^4 ohms,

$$i = 5.75 \times 10^{-13} \quad (\delta f)^{\frac{1}{2}}$$

approximating δf by $1/\delta t = 10^7$ cps,

$$i = 1.8 \times 10^{-9} \quad \text{coulombs/sec}$$

$$= 1.1 \times 10^{10} \quad \text{electrons/sec}$$

* RCA type C70102B; Westinghouse type WX-22779

** See Holter[2], p. 243.

OPTICAL FILTER

Since the next section will show that background radiation is a major cause of noise, it is desirable to filter out all wavelengths except those emitted by the laser itself. From Eq. (11), Chapter 2, it is seen that the fraction $\Delta\lambda/K_\lambda$ must be kept low, that is, the desirable filter will have a narrow passband to eliminate background and a high transmission to pass signal. The high transmission is always desirable, but if other noise in the circuit is much higher than background then only $1/K$ needs to be low. This is important since in manufacturing interference filters, transmission and bandpass features tend to be incompatible. Generally, in order to get sharper bandpasses more interference is necessary, implying more layers of the thin films and this of course means less transmission.

Spectrophotometer traces of the best available filters for 1.06μ are shown in Figs. 10 and 11. The first trace is over a long wavelength range to show the blocking and the next trace is expanded to show the bandpass region. This shows extended blocking over the visual range for the case when S-1 surface photomultiplier is used as this photomultiplier is sensitive in this wavelength range. Neither the photomultiplier nor the silicon detector is sensitive to wavelengths longer than 1.2μ.

From the graph, which is an actual trace, K_λ is seen to be 70%, and $\Delta\lambda$, measured at 35% transmission is 95Å. By summing numerically

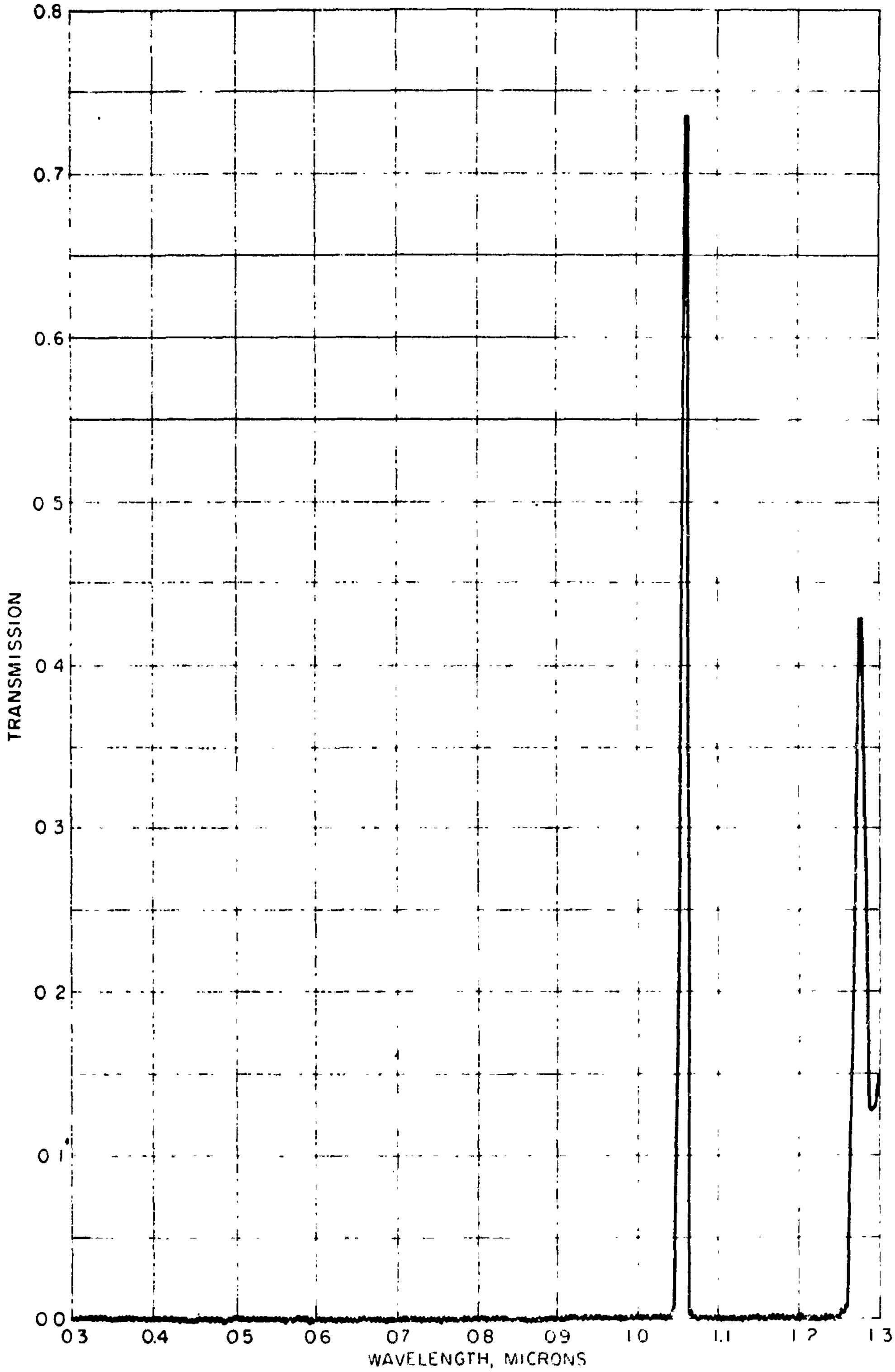


Figure 10. Bandpass Optical Filter

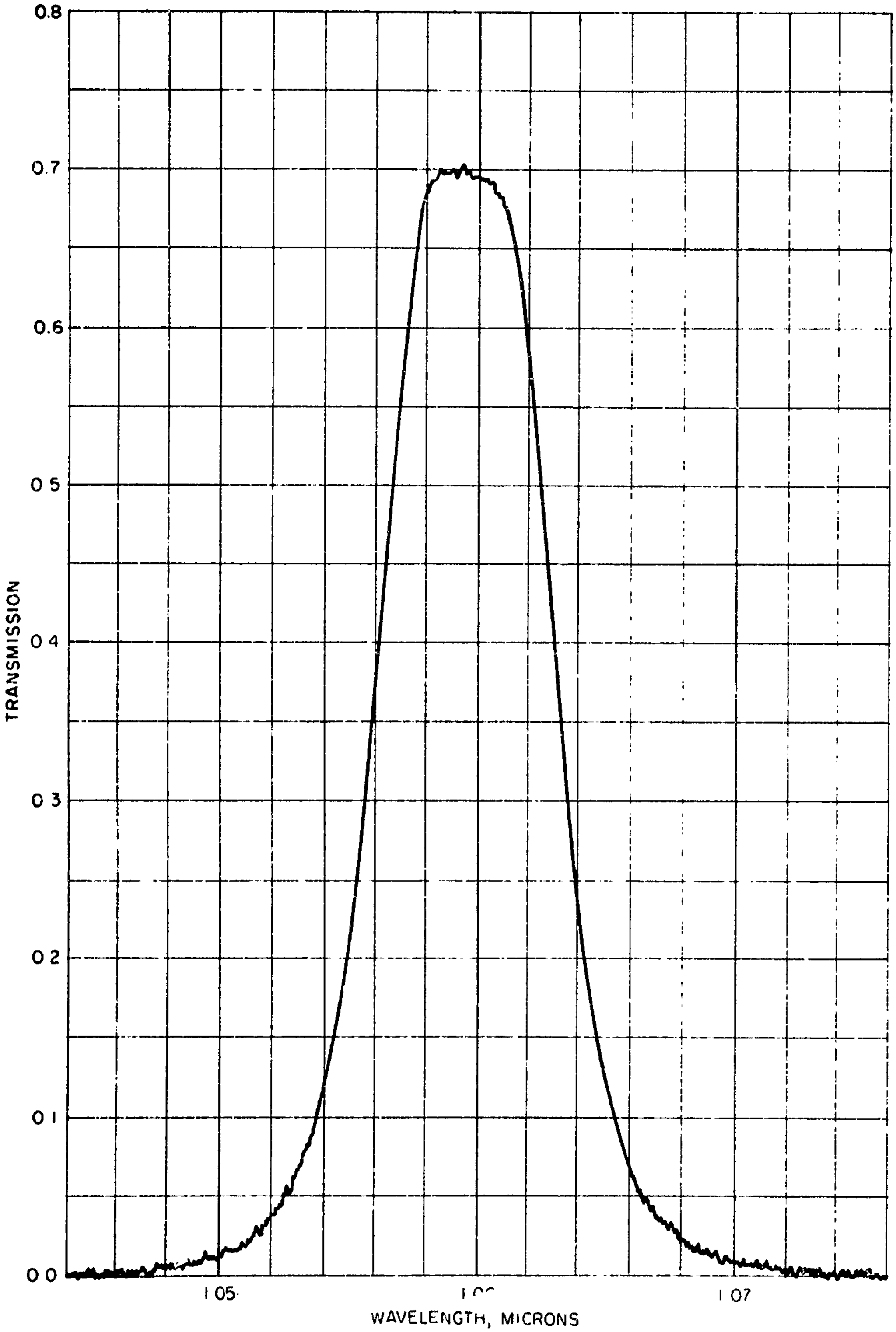


Figure 11. Bandpass Optical Filter (Expanded Scale)

as indicated in Chapter 2, it can be seen that this value for $\Delta\lambda$ is slightly low, so a rounded value of 100Å is used instead.

CALCULATION OF NOISE DUE TO BACKGROUND

Using 3 X 10^{-4} watts/ster-m^2-Å as the value for background radiation the noise can be calculated in terms of electrons coming from the detector. From Chapter 2, Eq. (2b),

$$I_n \text{ (electrons/sec)} = P_B \, A_R \, (\Omega_R - \omega_{OR}) \, \Delta\lambda \, K_\lambda \, K_R \, \eta \, \frac{\lambda}{h\,c}$$

All the variables except K_R and Ω_R have been determined and in the next chapter it will be shown that their values are .9 and $\pi/2 \times 10^{-6}$ steradians, respectively. Substitution of the appropriate values into the equation gives

$$I_n = \frac{(3 \times 10^{-4})(6.36 \times 10^{-3})(\frac{\pi}{2} - .5)(10^{-6}(100)(.70)(.9)(.5)(1.06 \times 10^{-6})}{(6.63 \times 10^{-34})(3 \times 10^{8})}$$

$= 34.4 \times 10^{7}$ electrons/sec

CALCULATION OF SIGNAL-TO-NOISE RATIO

Calculations show that during the resolution time δt $(= 10^{-7}$ sec) on the average 34.4 electrons will be expected from the detector. The fluctuations around this average value will be Gaussian, due to thermal noise, with a standard deviation s of 1.1 X 10^{3} electrons.

From the desired total false alarm rate $F_{\Delta t}$ of 0.001, the false alarm rate during δt is given from Eq. (5), Chapter 2.

$$F_{\Delta t} = 1 - (1 - F_{\delta t})^{z}$$

where

$$z = \frac{\Delta t}{\delta t} = \frac{2\ \Delta R\ /\ c}{2\ \delta R\ /\ c} = \frac{800\ \text{yds}}{50\ \text{ft}} = 49$$

thus

$$49\ \ln(1 - F_{\delta t}) = 0.9990$$

$$F_{\delta t} = 2.0 \times 10^{-6}$$

and from the Biometrika Tables[15] this is a 4.6 standard deviation. The decision level or threshold number of electrons is

(4)

$$n_t = \bar{n} + x\ s$$

$$= 34.4 + 4.6\ (1.1 \times 10^3)$$

$$= 5100 \text{ electrons}$$

However for a missed signal probability of $2\frac{1}{2}\%$ the average number of electrons in the signal must be 2.0 standard deviations of signal plus noise greater than n_t. Since the signal has a Poisson distribution, the standard deviation of the signal equals the square root of the mean $\bar{N}$. The standard deviation of noise is about equal to s since $\bar{n}$ is small. Thus the standard deviation of signal plus noise is approximately equal to

$$(\bar{N} + s^2)^{\frac{1}{2}} \approx s$$

and

$$\bar{N} \approx n_t + 2.0s$$

$$\bar{N} = 7300 \text{ electrons}$$

A graph is given, Fig. 12, for the rifle rangefinder showing the probability of the number of electrons occurring as current from the detector during the 10^{-7} seconds when a signal is expected. The probability of there being a noise pulse to the right of the decision level n_t is 0.1% and the probability of having the signal plus noise add up to less than n_t is 2.5%.

CALCULATION OF POWER REQUIREMENT

At the end of Chapter 2, Eq. 11 is used for background limited noise. Because in one case detector noise is also appreciable Eq. 10a is used and xs is determined from the combination of the two sources

(10a) $$P_T = \frac{\bar{N}\, \pi^2\, \theta^2\, R^4\, e^{2\alpha R}\, h\, c}{4\, A_0\, A_R\, K_T\, K_0\, K_R\, K\, \eta\, \lambda\, \delta t}$$

It will be seen (Chapter 4) that θ can be made small enough so that the ½ yard diameter object will be as large as the beam crosssection at 1000 yards. That is θ can be designed to be ½ milliradian. This means that $A = \pi(\theta\, R)^2/4$. In order to allow for the sniper to miss aim the laser so that only half the target is hit, a factor of two is inserted.

Thus $$P_T = \frac{2\, \bar{N}\, \pi\, R^2\, e^{2\alpha R}\, h\, c}{A_0\, K_T\, K_0\, K_R\, K\, \eta\, \lambda\, \delta t}$$

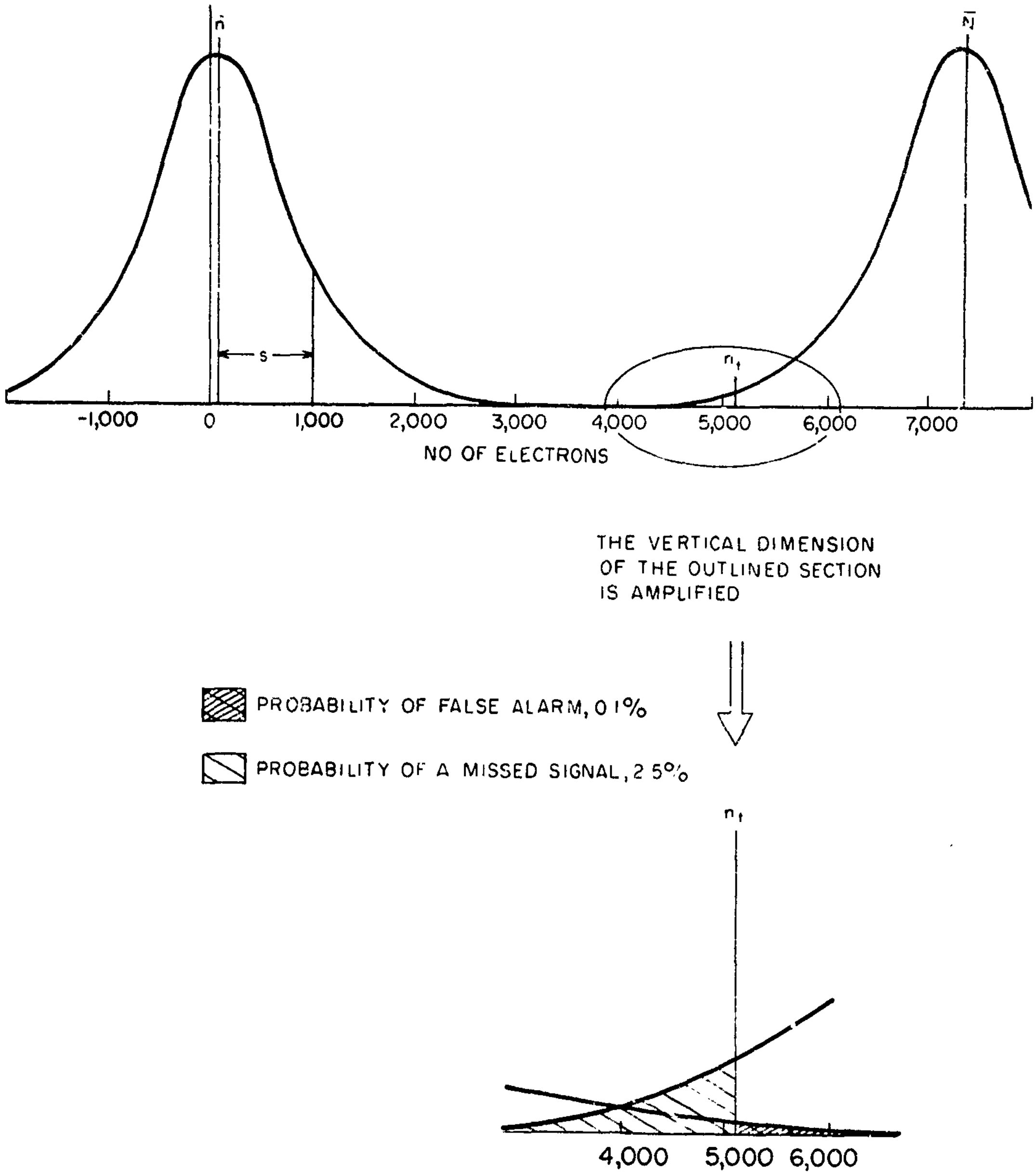


Figure 12. Probability Distribution of Electrons from Detector--Rifle Rangefinder

All values have been determined except K_R and K_T which will each turn out to be 0.9. Substituting the appropriate values gives

$$P_T = \frac{2\ (7300)\ \pi (914)^2 (.20)(6.63 \times 10^{-34})(8 \times 10^8)}{(6.36 \times 10^{-3})(.9)(.1)(.9)(.70)(.5)(1.06 \times 10^{-6})(10^{-7})}$$

$$= 190 \text{ watts}$$

P_T is to be interpreted as being the average power delivered in 10^{-7} seconds; that is, the energy is to be 19×10^{-6} joules in 10^{-7} seconds. Since a typical Q-spoiled pulse is shorter than δt in this case the peak power of the pulse may be more than P_T. If the rise time of the detector and the components in the associated circuitry were faster than 10^{-7} seconds, then the average power would not need to be so high and advantage could be taken of the short laser pulse and correspondingly higher peak power. This however has been difficult to accomplish on the first prototype. Hopefully future models will allow more time to be spent in developing the electronics.

Chapter 4

INTRODUCTION

This chapter outlines the design for the rifle rangefinder. Space does not permit a complete evolution of each part with reasons for discarding each possible idea for a better one, however a reasonably complete description of each component in the present, prototype design, is presented.

The design can be examined under five major headings: Laser, Optical Design, Detector, Timing Circuit and Display, and Power Supply.

LASER

The requirements for the laser transmitter are that it produce 19 microjoules in less than 10^{-7} seconds (it is allowed to continue emission for longer than 10^{-7} seconds but the start of this time period is begun with the first light emitted and therefore a Q-spoiled laser is implied), that it be made of neodymium-glass, that it be as well collimated as is practically possible, that it have high

efficiency in converting battery power to light output, and above all that it be small, reliable, rugged and easily operated.

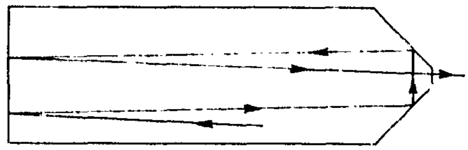
Up until the time that the rest of the design had already been completed the laser was a big problem requiring much thought and laboratory experimentation. The method of Q-spoiling was the cause of concern. Up until then the device consisted of a prism on a cocked spring with possibly a Lummer-Gehrke[25] type arrangement to sharpen the in-alignment time of the prism. Then when the rest of the design was all but complete, news of a major break-through in Q-spoiling lasers was announced;[26-28] this made the job easy because the advantages were so definite that a contract was simply placed with one of the companies making the discovery to supply a complete laser with the above specifications. Basically the discovery consists of a piece of material about one cm long and of the same diameter as the neodymium rod which is placed with the rod, inside the resonating laser cavity. Of the three groups having early results with the discovery, only Lear-Siegler was able to obtain material which would work at 1.06μ; their material is a specially doped uranium glass. The other two companies, Korad, Inc. and International Business Machines have a liquid held in a glass cell which works well for the ruby wavelength. Phenomenally the material works by being almost opague as the neodymium-glass is being pumped to the excited state thus spoiling the Q (Q stands for quality) of the cavity. When the excitation level is sufficiently high the material undergoes a photochemical change and becomes clear allowing the giant pulse to be emitted. It remains clear so long as the flux through it is high enough, that is, until the excited energy level

has been entirely depleted, and then becomes dark again ready to repeat the process. The method is entirely passive mechanically with no moving parts or input trigger signal; it is compact and rugged and its efficiency is higher than any previous Q-spoiler. While other methods do not switch the Q very efficiently and also require auxiliary power to supply a pulse or run a motor, this "saturable filter" has neither shortcoming. The glass requires a negligibly small percent of the flashtube energy to populate an excited state above the ground state which is then saturated, while the liquid requires no pump power at all.

Standard techniques are used for the flashtube and reflector. It has been found that not only the smallest configuration, but also an extremely efficient method is to have a linear flashtube in contact with the laser rod and a cylindrical reflector fitted as tightly around them as practicable.

The resonant ends of the laser cavity will be totally internally reflecting roof prisms, one end made on the laser rod and the other on the saturable filter. One end will have a flat polished on the apex of the roof for the light to exit. This eliminates any thin-film surfaces which might deteriorate or move out of alignment and also serves a purpose to be described in the next section. This is a relatively new method for extracting the energy from the laser cavity and is not completely understood. At first glance one would suppose that no resonance nor standing waves could be sustained in the region of the truncation at all. The efficiency, however, appears to be about as good as other forms of output coupling. A possible

explanation might be to describe all the lasing to off-axis modes of resonance as shown here.



It is calculated that the minimum possible input which will still cause lasing action gives an output which is more than that required for P_T. Thus rather than expending efforts to increase the output the primary development needs to be to decrease the threshold energy necessary for lasing.

The exit beam spread from the laser will be about 3 milliradians and will therefore need to be recollimated to decrease this divergence.

OPTICAL DESIGN*

In a typical laser rangefinder there are three distinct optical systems performing separate tasks. One is a telescopic sight for aiming the laser, one is a return energy-collection system, and the third is a system which takes the light as it comes from the laser and projects it with decreased divergence.

It would be advantageous if these three sets of optics (particularly the large, heavy objective lenses) could be synthesized in some way. The sighting scope can easily be combined by the use of a dichroic mirror since the laser wavelength, 1.06μ, is outside the

* Much of this section on Optical Design has been published previously by the author in a Naval Ordnance Test Station Technical Publication (see reference 8) and in an invention disclosure to the Navy.

visual wavelengths. The dichroic mirror is placed behind the objective lens to reflect the visual but transmit the infrared wavelengths. The reflected light then goes to the eyepiece in the usual manner.

The two remaining functions are combined as follows. Using the truncated prism described in the preceding section for the output, the laser light is focused to a point, producing either a real or a virtual image. As the source is monochromatic and axial, aberrations other than spherical do not exist. The best shape for the lens can be found by minimizing spherical aberration according to the following relationship.

$$\left(\frac{r_1}{r_2}\right)_{min} = \left(\frac{2n^2 - n - 4}{2n^2 + 1}\right) \tag{13}$$

Where

n = the glass index

r_1 = the radius of curvature of the lens surface on the side facing the collimated light

r_2 = the radius of the opposite side

For glasses in the visual region, this gives a lens of nearly plano-convex or -concave shape (for the sake of compactness a negative lens is used). The point of light formed by this negative lens is adjusted to be on the axis and at the focus of the objective lens, and the laser radiation is then projected with a collimation better than the original collimation by the ratio of the diameter of the

objective lens to the diameter of the laser rod. However, not this much gain is achieved when aberrations become important or when the circle of least confusion is diffraction-limited.

Light coming back from the target will come back through the same system; some will reenter the apex of the prism, but most of it will be reflected to the side by a mirror with a hole in the center as shown in Fig. 13, and focused onto the detector. For a large objective lens, aberrations will bother less if only part of the lens is used for the projector. In collecting the light where aberrations are not nearly so important, however, the whole lens is used and the area of the truncation now takes up a smaller percentage of the cross section of the light beam. Also, a high quality lens can be used with a plastic aspherical lens as an annulus surrounding it, thus further decreasing equipment weight and cost. The other lens is threaded into the plastic, adjusted until the foci match, and then fixed permanently in place.

To determine actual dimensions involved, ray-trace data were used and the contribution of spherical aberration to the lateral image dimension was calculated for several indices. The result is plotted as a function of the f/no. of the cone, Fig. 14. The ordinate is given as a percentage of the plano-concave lens diameter, which in turn is defined by the diameter of the laser rod. As seen from the graphs on the next page, a plano-concave lens can be designed so that spherical aberration is negligible and strict adherence to Eq. (13)

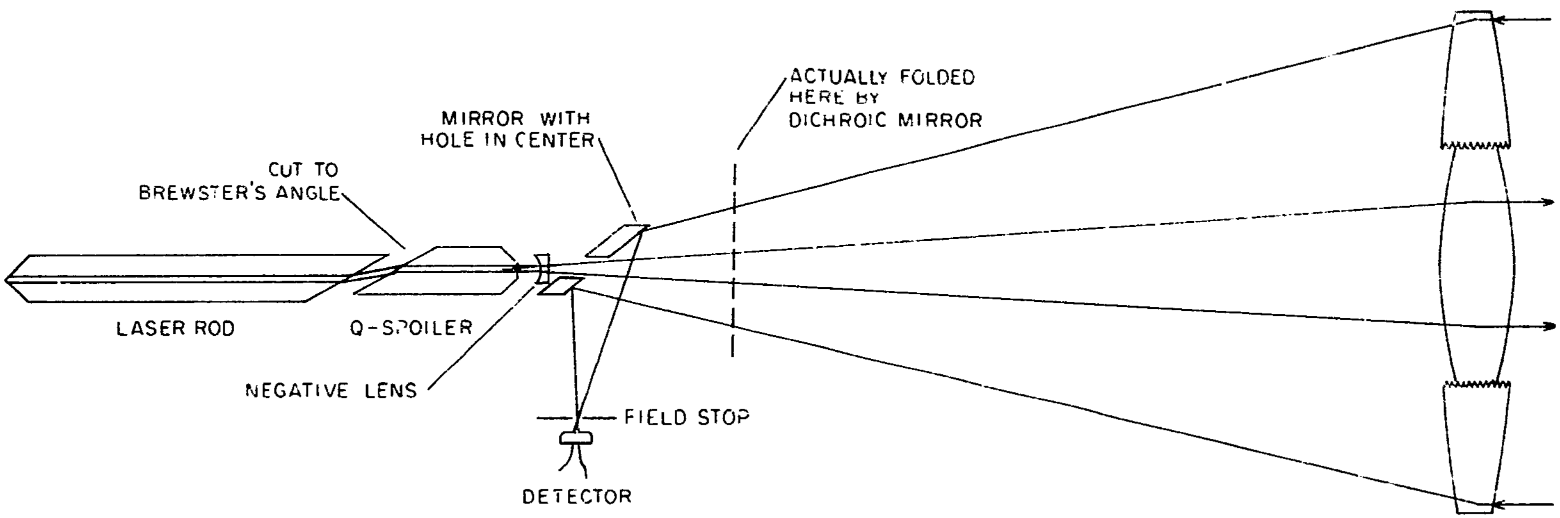


Figure 13. Laser Transmit-Receive Optics

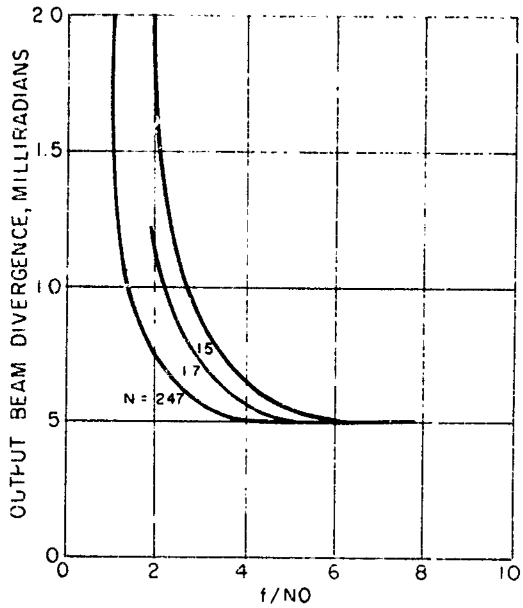


Figure 14

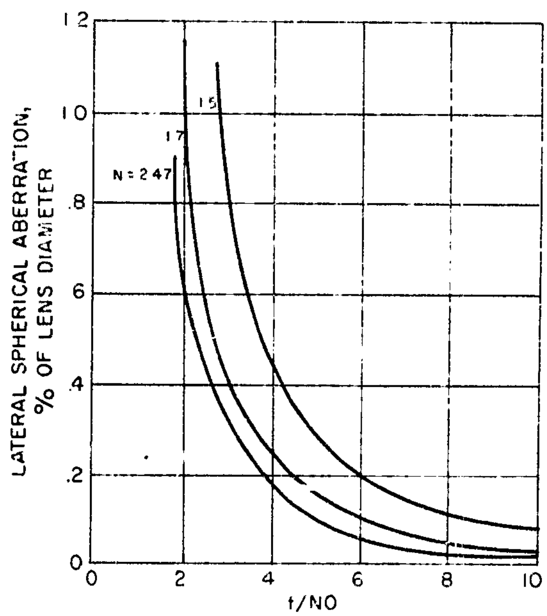


Figure 15

is not necessary. That is, Eq. (13) may show that the radii should be in the ratio of 6:1, but the ray trace data show that plano-concave radii approximate this ratio closely enough.

To be more specific, the output divergence was calculated for a 6mm diameter laser rod having a natural divergence of 4 mrad. The output divergence is recollimated by an optical system with a 50mm objective lens. As divergence approaches the asymptote, it is diffraction-limited and the spherical aberration serves only to redistribute the light within the diffraction image, putting more light into the rings instead of into the central disc.* Let the output divergence be labeled θ; then, for the first part of the curve:

$$\theta = \frac{\phi \times f/no. \times d + s.a.}{f/no. \times D} \tag{14}$$

Where

d = the diameter of the laser rod

D = the diameter of the objective lens

ϕ = the natural divergence of the laser rod

s.a. = the diameter of the blur circule due to spherical aberration.

For the asymptote part of the curve (where λ is the laser wavelength):

$$\theta = \frac{\phi \times f/no. \times d + 1.22\ \lambda/d}{f/no. \times D} \tag{15}$$

* A more detailed discussion of the tolerance for spherical aberration and the Rayleigh limit appears in Conrady[2]. See ref. 29.

At the crossover point between Eqs. (14) and (15), the value will be somewhat less than that given by Eq. (14).

It is felt that the minimum resolution possible, without a great deal of expense, for the aspheric, plastic collecting lens annulus is about 2 milliradians. The expense is not justified since background is not the limiting noise and decreasing background noise does not decrease the total noise significantly. A field stop is placed at the receiver focus to exclude any light other than that in the 2 milliradian field-of-view from hitting the detector.

Referring to Fig. 16 it is seen that the electroscope fiber (to be discussed), which gives the range readout, is imaged directly into the telescope eyepiece. The beamsplitter reflects about 30% of the light and transmits the rest. The fiber and reticle are seen only when illuminated by a light behind the fiber.

DETECTOR

The detector has been discussed in Chapter 3. The active element in the detection process is silicon which is specially "tuned" so that its wavelength of maximum response is 1.06μ. It is followed by an amplifier with an overall gain of 200. The transistors in the first stage of the amplifier are to be mounted directly with the detector at the focus of the collection optics and succeeding stages are connected by a 10 cm cable so they can be located more conveniently.

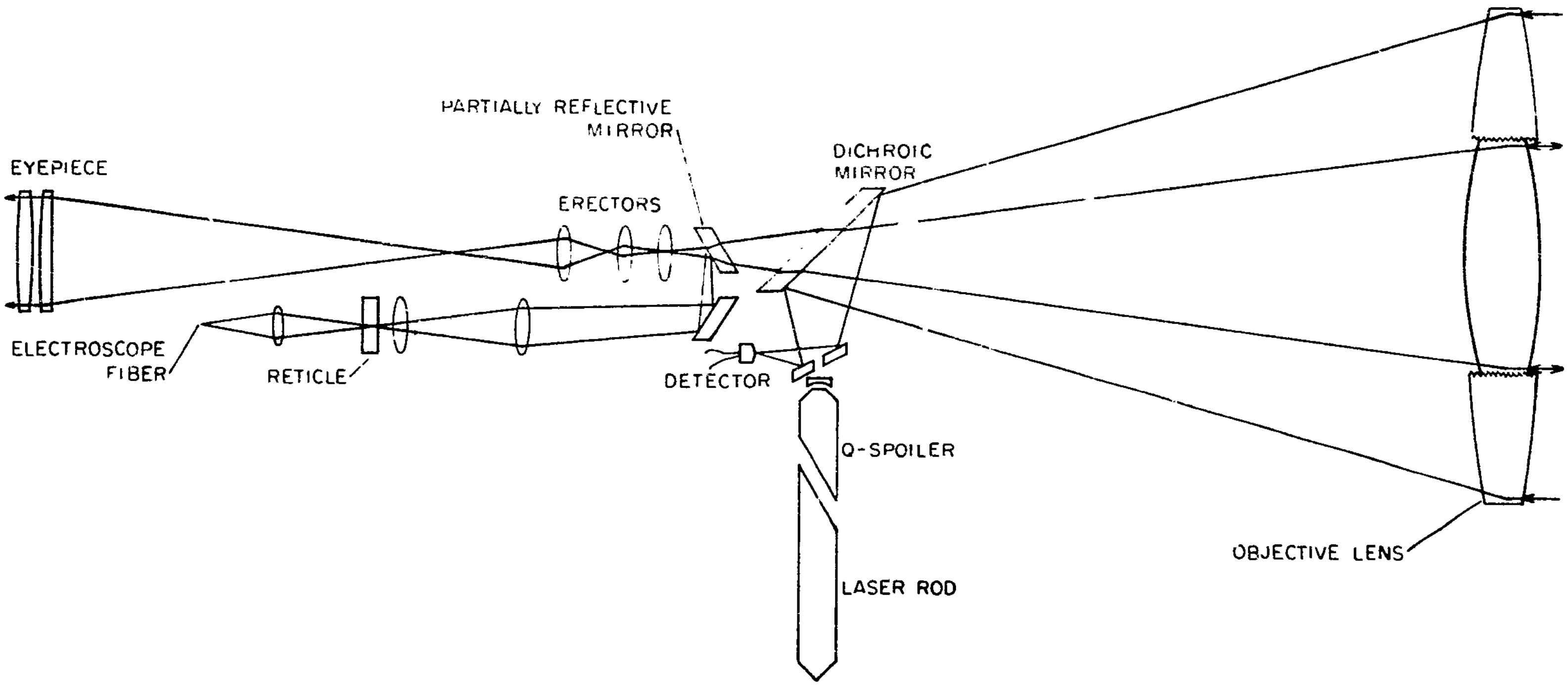
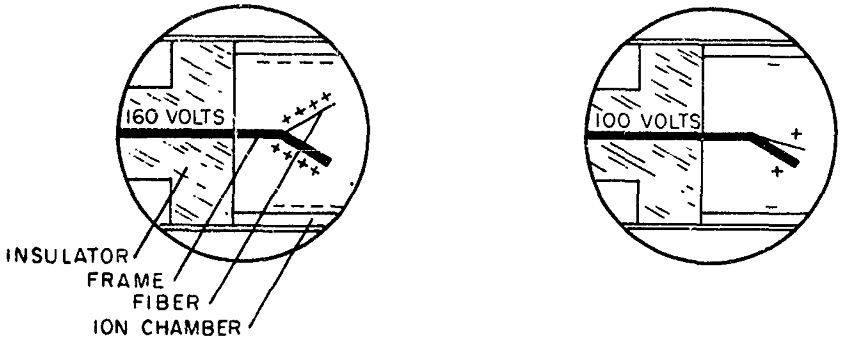


Figure 16. Rangefinder Optical System

TIMING CIRCUIT AND DISPLAY

The method used to display range information has been worked out jointly by the author and Dr. Julian L. Thompson. In searching for a method the advantages of a nuclear dosimeter were explored. The dosimeter in mind is one designed to be worn in a person's pocket to measure the integrated exposure to ionizing radiation. It consists of a metal coated quartz fiber supported on a metal frame as shown in Fig. 17 with a surface surrounding the frame and fiber. The fiber acts like an electrometer so that in the case of the dosimeter which is used (Bendix Corporation) the fiber is close to the frame when there is 100 volts potential difference between the chamber and the fiber and frame. When the fiber and frame are charged to 160 volts becoming more positive with respect to the chamber, the fiber is repelled by the frame and moves toward the ion chamber walls. The fiber is imaged by a lens onto a reticle or scale. When it is used as a dosimeter incoming radiation ionizes the chamber and the fiber thus records the total dosage of radiation received. Used as a dosimeter the maximum electrical leakage is $1\frac{1}{2}\%$ of full scale for 24 hours. A maximum change in sensitivity of $\pm 10\%$ may occur under any probable combination of: (a) temperature range of -40°F to +150°F, (b) 50,000 feet altitude, or (c) 100% relative humidity. The units are small in size, withstand high shock and vibration and weigh only one ounce.

A unit is designed in the circuit to act as a voltmeter and the scale is changed to read increments of range. In addition to the



Charged **Uncharged**

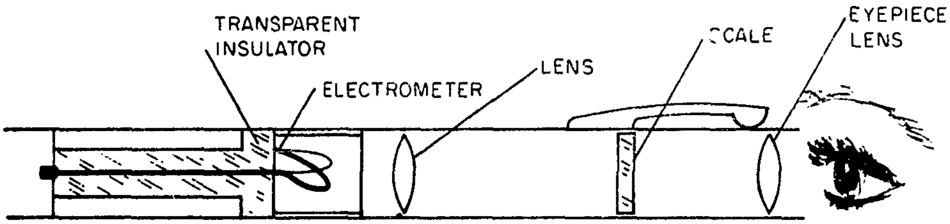


Figure 17. Simplified Cross Section of Bendix Dosimeter

advantages apparent from the above features, the image of the quartz fiber is designed to be displayed directly in the eyepiece of the riflescope whenever an illumination light is turned on. This allows the sniper to keep his eye on the target while reading the range. It is also possible with a cam arrangement to set automatically the proper elevation into the scope without taking the eye from the scope by matching a needle to the fiber image in a manner similar to the way an automatic camera sets the iris for varying exposure illumination. The fiber arrangement requires no power such as is necessary to illuminate nixie tubes or drive mechanical counters and has an extremely simple accompanying circuit which therefore will be smaller and more reliable.

When used in a timing circuit the fiber is set to read the amount of charge present on a capacitor (see the electronic diagram, Fig. 18). The capacitor has a high voltage supply which is turned on by the flip-flop circuit when the laser fires. The capacitor then begins charging and stops when the return light pulse is received and put into the flip-flop circuit. The amount of charge on the capacitor is then read on the dosimeter reticle as range in yards.

Actually the flip-flop gates-on a transistor as shown which completes the circuit to the high voltage supply. When the transistor is gated off again the capacitor would normally just discharge back through the transistor; instead a high-speed diode is placed in the discharge path. Diodes are fast enough to catch the capacitor at the peak of its charge and hold it there, but the best diode that could be found still had a leak rate which allowed the capacitor to slowly

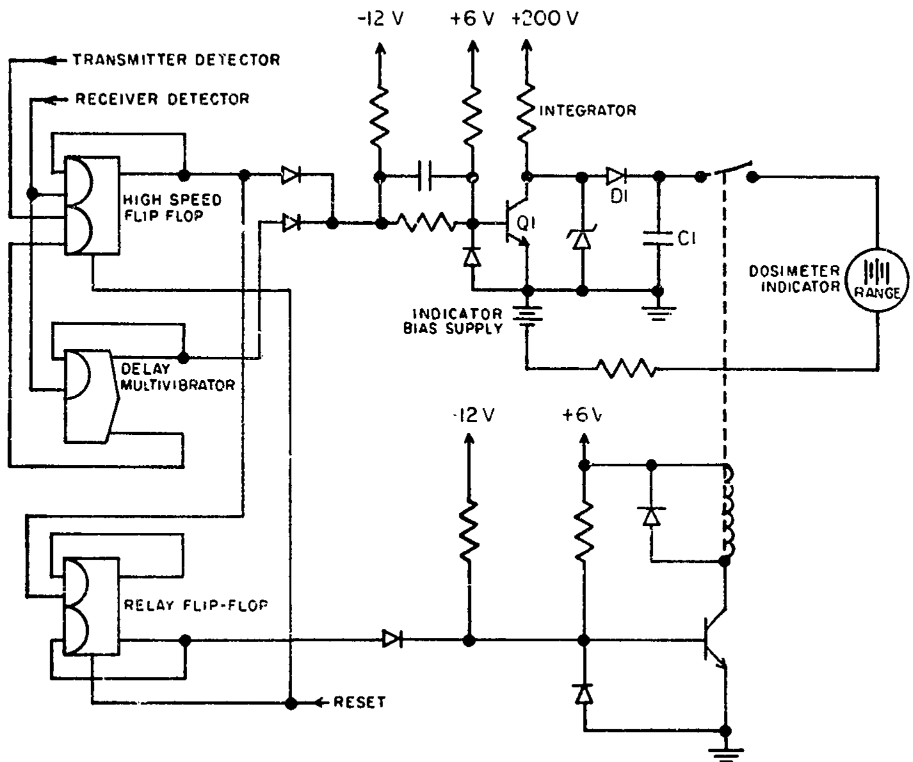


Figure 18. Timing and Display Circuitry

discharge in 10 or 20 seconds since leakage of only a few electrons causes a high percentage change in the small capacitor and in the dosimeter. This would require the sniper to make an instantaneous reading of range. To circumvent this difficulty a miniature reed relay is put in series with the diode. While the reed switch is not fast enough to do the job of the diode (the diode needs to be faster than 10^{-7} seconds, the reed switches in about a millisecond) it doesn't leak since the contacts are mechanically separated; and the two of them together do the job that neither could do alone.

When the laser fires, some of the transmitted light along the beam is scattered in all directions, some of it back toward the receiver. At close ranges this is enough to be detected and would give a false signal. Since range is required only from 200 to 1000 yards, a delay circuit is introduced to keep the flip-flop from accepting a second pulse for the first 200 yards of range, and the first reading on the reticle is a 200 yard mark.

POWER SUPPLY

The voltages and current needed are listed below per laser firing. It is felt that the rangefinder should be designed to give 50 shots before the batteries are to be recharged. Provision is made to recharge the batteries from standard military vehicle batteries, which are 24 volts. Silver-zinc batteries are used because of their superior energy to weight ratio. The batteries and capacitors are housed in the rifle stock.

Required per pulse	Use
$+2500 \pm 500$ volts negligible energy	Trigger voltage for flashtube
$+450 \pm 5$ volts 50 joules	Laser flashtube. Capacitors releasing 50 j per pulse will be charged in ten seconds, previous to using the laser.
$+200 \pm 1$ volt 20 joules	High voltage for timing capacitor
+12 volts battery supply 140 joules	Timing circuit - 120 joules Detector and amplifier supply - 20 joules
$-100 \pm .5$ volts negligible energy	Dosimeter bias supply

The total energy required is 210 joules/pulse X 50 pulses = 10500 joules. A 12 volt battery is planned with voltage converters to provide other voltages. The battery required will thus be

$$\frac{10500 \text{ joules}}{3600 \text{ sec/min} \times 12 \text{ v}} = 0.25 \text{ ampere hours.}$$

A silver-zinc battery rated at a nominal 0.5 ampere hours and consisting of 8 cells will provide this and will be rechargeable 20 to 40 times; it would weigh 6.4 ounces and have an overall volume of 7.3 cubic inches.

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ABSTRACT. In order to design a laser rangefinder, it is necessary to predict the effect that a change of any variables will have on the expected performance. Preliminary aspects of the overall design are discussed giving a general background in the current state of the art. A derivation of the relationship

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